IAEA Contract No. 10308/RO

A Progress Report

Testing and improvements of gamma-ray strength functions for nuclear model calculations of nuclear data

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July 1998-July 1999

Kiev

SUMMARY

A closed-form thermodynamic pole approach, TPA, is developed for average description of the E1 radiative strength functions using the microcanonical ensemble for initial states. The method can be applied to calculate the dipole strengths in heated and cold nuclei for processes of the gamma-decay as well as photoabsorption in a unified way. A semiclassical description of the collective excitation damping in the TPA method is based on modern physical notion on the relaxation processes in Fermi systems. The strengths within TPA approach depends on the excitation energy, i.e. Brink hypothesis is violated in this method.

The TPA calculations were compared with experimental data and calculations within the EGLO method which is recommended by the IAEA as the best practical model for calculation of the E1 strength. It is shown that the TPA model is able to cover a relatively wide energy interval, ranging from zeroth gamma-ray energy to values above GDR peak energy. It gives rather accurate means of simultaneous description of the γ - decay and photoabsorption strength functions in the medium and heavy nuclei. The results obtained by EGLO and TPA approaches are almost the same at low energies $\epsilon_\gamma \lesssim 3MeV$. In this range the EGLO and TPA models describe experimental data much better than the standard Lorentzian model, SLO, and give a non-zero temperature- dependent limit of the strength function for vanishing gamma-ray energy. For gamma-ray energies near neutron binding energies the calculations within the TPA model describe experimental data somewhat better for heavy nuclei with $A \gtrsim 150$ as compared to other closed-form approaches. The set of the best parameters for TPA calculations of the E1 strengths in heavy nuclei is determined. The further investigations are important to refine dependence of the collisional and fragmentation components of the strength function width on gamma-ray energy and mass number.

The computer codes were created for the calculations and plotting of the radiative strength functions. The E1 strength are calculated within framework of the SLO, EGLO and TPA models as a function of gamma-ray energies or mass number. The codes made under MS-DOS and Windows 3.1X/9X operating systems are written in Fortran and Delphi programming languages. An option of visual comparison between the calculations and experimental data is included.

INTRODUCTION

Gamma-emission is one of the most universal channel of the nuclear decay, because it generally may attend any nuclear reaction. This process as well as absorption of the gamma-rays and electron - positron decay are described in the many-body systems by the radiative strength functions ([1] - [3]). These functions are important for the study of the nuclear structure models, γ-decay mechanisms, deformation and fluctuation of the nuclear shape, energies and widths of the collective excitations ([4] - [9]). Besides this fundamental importance from a theoretical point of view, the strength functions are necessary to generate the data for the energy and non- energy applications. It is critically important to have a simple closed-form expression for the γ - ray strength function because in most cases this function is an auxiliary quantity used in calculations of different nuclear characteristics and processes. The theory-based approaches for γ- strength are preferred over the empirical ones to improve the reliability and accuracy of such calculations and to understand the physical sense of used parameters.

According to Brink hypothesis[10, 11], the Lorentzian line shape with the energy- independent width (SLO model) is widely used for calculations of the dipole ($E1$) radiative strength. This approach is most appropriate simple method for the description of the photoabsorption data on medium and heavy nuclei ([12] - [14]). The situation is more complicated in the case of the gamma-emission. The SLO model strongly underestimates the gamma-ray spectra at low energies $\epsilon_\gamma \lesssim 1MeV$ [15, 16]. A global description of the gamma-spectra by the Lorentzian can be obtained rather satisfactorily in the range $1 \lesssim \epsilon_\gamma \lesssim 8MeV$ but with use of the giant dipole resonance (GDR) parameters which are different from those based on photoabsorption data. On the whole, SLO approach overestimates the integral experimental data (the capture cross sections, the average radiative widths) in heavy nuclei ([14] - [21]). The models for description of the $E1$ strengths at low energies ϵ_γ were proposed in Refs.[22, 23]. An enhanced generalized Lorentzian model (EGLO) was used and analyzed in Refs.[24, 25] for a unified description of the low energy and integral data. The EGLO radiative strength function consists of two components (for spherical nuclei): a Lorentzian with the energy and temperature dependent width $\Gamma_k(\epsilon_\gamma, T)$, and finite value term from [22] corresponding to zero value of γ - ray energy. An empirical expression for width $\Gamma_k(\epsilon_\gamma, T)$ was used with two additional parameters. The dependence of the parameters on mass number was obtained to fit EGLO calculations to the experimental data. Nowadays the EGLO method is recommended by the IAEA [25] as the best practical model for calculation of the dipole gamma - ray strength function when the experimental data are unavailable.

It should be noted that the SLO and EGLO expressions for the gamma-decay strength function of heated nuclei are in fact the parametrizations of the experimental data, namely,

1) these expressions are not consistent with general relation between strength function and the imaginary part of the response function of the heated nuclei (see [26] - [28] and Sect.2);

2) the EGLO damping width Γ_k has the empirical dependences on γ-energy and temperature T. It is similar to the one of the zero sound damping in the infinite fermi- liquid when

the collisional (two-body) dissipation is taken into account only. It is well known that an important contribution to the total width in heavy nuclei is given by the fragmentation (one - body) width which determines a redistribution of the particle- hole excitations near of the collective state ([29] - [31]). The latter component of the width is almost independent of the nuclear temperature. The width of the SLO model can be identified with this fragmentation component.

The statistical description of the average γ - decay strength of excited states is presented below using the microcanonical ensemble for initial states. The contributions to the relaxation width resulting from the both interparticle collisions with retardation effects and fragmentation are taken into account in a semiclassical way. The dependences of the γ - decay and photoabsorption strength functions on the initial excitation energy, the gamma-ray energy and mass number are investigated within the thermodynamic pole approximation (TPA method). The TPA calculations are compared with those ones within EGLO, SLO models and with the experimental data. It is shown that the TPA model is able to cover a relatively wide energy interval, ranging from zeroth gamma-ray energy to values above GDR peak energy. It gives rather accurate method of simultaneous description of the γ - decay and photoabsorption strength functions in the medium and heavy nuclei.

GAMMA -RAY STRENGTH FUNCTIONS IN HEATED NUCLEI

We shall consider the radiative strength function averaged over spins of initial states for γ - emission of the electric type with the energy ϵ_γ and multipolarity λ. The general expression for this function can be obtained from the relation for the average radiative width $\bar{\Gamma}(\epsilon_\gamma)$ per unit of the γ - ray energy interval [32]. Within statistical mechanics the width $\bar{\Gamma}(\epsilon_\gamma)$ is defined in standard way as the quantity averaged over states with slightly different values of the total initial energy E and numbers of protons Z and neutrons N

$$\bar{\Gamma}_\lambda(\epsilon_\gamma) = \sum_{J,M,\Delta E,\Delta Z,\Delta N,J_f} [\frac{d\Gamma_{if}}{d\epsilon_\gamma}]/\mathcal{N}, \tag{1}$$

where $\mathcal{N} = \sum_J \omega(E,Z,N,J)\Delta E\Delta Z\Delta N$ is the total number of initial states; $\omega(U,Z,N,J)$ is the density of states; $U = E - E_0$ is the initial excitation energy ; E_0 is the ground state energy. The quantities J and M are the spin of initial states and its projection on the Z axis, respectively; ΔE, ΔZ, ΔN are the small - scale intervals of the dispersion in values of the energy, numbers of protons and neutrons near the average values E, Z, N.

The quantity

$$d\Gamma_{if}/d\epsilon_\gamma \equiv d_\lambda(\epsilon_\gamma)B_{if}^{(\lambda)}\delta(E - E_f - \epsilon_\gamma)$$

is the γ - transition probability with the energy ϵ_γ from an initial state i to the final state f; $d_\lambda(\epsilon_\gamma) = (\epsilon_\gamma/\hbar c)^{(2\lambda+1)}8\pi(\lambda+1)/(\lambda[(2\lambda+1)!!]^2)$, and

$$B_{if}^{(\lambda)} = \sum_{M_f,\mu} |< J_f M_f E_f \mid Q_{\lambda\mu} \mid JME >|^2$$

is the reduced transition probability with the multipole operator $Q_{\lambda\mu}$ for $E\lambda$ radiation,

$$Q_{\lambda\mu} \equiv \sum_k e_k(\lambda)\ r_k^\lambda\ Y_{\lambda\mu}(\hat{r}_k),$$

$$e_n(\lambda) = e(-1)^\lambda Z/A^\lambda, \quad e_p(\lambda) = e[(A-1)^\lambda + (-1)^\lambda(Z-1)]/A^\lambda.$$

The quantities $e_n(\lambda)$ and $e_p(\lambda)$ are the effective kinematic charge of the neutrons and protons in nucleus, respectively.

Eq.(1) can be represented in the following form

$$\bar{\Gamma}_\lambda(\epsilon_\gamma) =< D(\epsilon_\gamma) > /\Omega(U, Z, N). \tag{2}$$

Here, $\Omega(U, Z, N) = \sum_J \omega(U, Z, N, J)$ is the total density of the initial states; the symbol $< \ldots >$ denotes an average over the energies and numbers of the protons and neutrons with the unit weight functions in the intervals ΔE, ΔZ and ΔN, respectively;

$$D(\epsilon_\gamma) = d_\lambda(\epsilon_\gamma) \sum_{N',Z',J,M,J_f,M_f,\nu} \delta(E - E_\nu)\delta(N - N')\delta(Z - Z')\times$$

$$|< J_f M_f E_f \mid Q_\lambda \mid JME >|^2\ \delta(E_\nu - E_f - \epsilon_\gamma - \gamma_1(N - N') - \gamma_2(Z - Z')), \tag{3}$$

where $Q_\lambda \equiv \sum_\mu Q_{\lambda\mu}$. The identical changing the arguments is made in the δ - function depending on energy. The additional constants γ_i defined below fix the numbers of the protons and neutrons.

In the region of high excitation energies being discussed the density of states in the intervals ΔE, ΔN, ΔZ is almost constant. Therefore, we can assume that the D varies a little and $< D >= D$. In this case the quantity $\bar{\Gamma}_\lambda(\epsilon_\gamma) = D/\Omega$ coincides with the width of the γ - decay of states of the microcanonical ensemble with the given constants of motion E, Z and N. Using the integral representation of the δ - functions

$$\delta(x) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} dt \exp(itx), \tag{4}$$

and completeness relation for wave functions one obtains

$$D(\epsilon_\gamma) = \frac{1}{(2\pi)^3}\int_{-i\infty}^{+i\infty} d\alpha_1 d\alpha_2 d\alpha_3 \exp(\alpha_3 U - \alpha_1 N - \alpha_2 Z)\mathcal{Z}(\{\alpha_j\})\Gamma(\{\alpha_j\}, \epsilon_\gamma). \tag{5}$$

Here, $\mathcal{Z}(\{\alpha_j\}) = Sp(\exp(-\beta\mathcal{H}))$ is the partition function of the grand canonical ensemble characterized by three constants $\alpha_1, \alpha_2, \beta \equiv \alpha_3$; $\mathcal{H} = H - \gamma_1\hat{N} - \gamma_2\hat{Z}$, $\gamma_j = \alpha_j/\beta$, H is the nuclear Hamiltonian and $\hat{N}$, $\hat{Z}$ are the operators of the neutron and proton numbers. The quantity $\Gamma(\epsilon_\gamma, \{\alpha_j\})$ is the mean width per unit energy of the γ decay of the states of the canonical ensemble with the parameters $\{\alpha_j\}$

$$\Gamma(\{\alpha_j\}, \epsilon_\gamma) = \frac{d_\lambda(\epsilon_\gamma)}{\pi} I_{Q_\lambda^*, Q_\lambda}(\{\alpha_j\}, \omega), \quad \omega = \epsilon_\gamma/\hbar, \tag{6}$$

where

$$I_{Q^*_\lambda,Q_\lambda}(\{\alpha_j\},\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} dt\ Sp[\rho(\mathcal{H})Q_\lambda(0)Q^*_\lambda(t)]\exp\{i\omega t\} \tag{7}$$

is the spectral intensity for the expectation value of the product $Q_\lambda(0)Q^*_\lambda(t)$ the multipole operator $Q_\lambda(t)$ in the Heisenberg representation

$$Q_\lambda(t) = \exp[it\mathcal{H}/\hbar]Q_\lambda \exp[-it\mathcal{H}/\hbar], \quad Q_\lambda \equiv Q_\lambda(0),$$

i.e. the time-depended correlation function for the operator $Q_\lambda(t)$. The canonical average $Sp[\rho(\mathcal{H})\ldots]$ is taken over the Gibbs ensemble with the density matrix $\rho(\mathcal{H}) = \exp[-\beta\mathcal{H}]/\mathcal{Z}(\{\alpha_j\})$.

Taking into account the fluctuation- dissipative relation between the spectral density of nonsymmetrized correlation function and response function [33, 34], Eq.(6) can be written as

$$\Gamma(\{\alpha_j\},\epsilon_\gamma) = s_\lambda(\epsilon_\gamma,\{\alpha_j\})\exp\{-\beta\hbar\omega\}, \tag{8}$$

where

$$s_\lambda(\epsilon_\gamma,\{\alpha_j\}) \equiv \frac{d_\lambda(\epsilon_\gamma)}{\pi} I_{Q^*_\lambda,Q_\lambda}(\{\alpha_j\},\omega)\exp\{\beta\hbar\omega\} =$$
$$-[d_\lambda(\epsilon_\gamma)/\pi](1-\exp\{-\beta\hbar\omega\})^{-1} Im\chi_\lambda(\omega,\{\alpha_j\}). \tag{9}$$

The quantity χ_λ is the linear response function given by

$$\begin{aligned}\chi_\lambda(\omega,\{\alpha_j\}) &= Ze_p(\lambda)\chi^{(p)}_\lambda(\omega,\{\alpha_j\}) + Ne_n(\lambda)\chi^{(n)}_\lambda(\omega,\{\alpha_j\}),\\ \chi^{(k)}_\lambda(\omega,\{\alpha_j\}) &\equiv Sp(r^\lambda\sum_\mu Y^*_{\lambda\mu}(\hat{r})\delta n_k)/q_\omega(t),\end{aligned} \tag{10}$$

where $\delta n_k(t)$ is the change of the single-particle density matrix n_k induced by the external field

$$V^k_{ext} = q_\omega(t)e_k(\lambda)r^\lambda\sum_\mu Y_{\lambda\mu}(\hat{r}), \quad q_\omega(t) = q_0\exp[-i(\omega+i\eta)t], \quad \eta\to+0, \quad q_0 \ll 1$$

for protons ($k = p$) and neutrons ($k = n$).

The integral in Eq.(5) can be evaluated by means of the saddle- point method. The parameters $\{\alpha_j\}$ of the saddle point are found from the condition of an extremum of the logarithm of the integrand. They are the solutions of the equations

$$\partial S_\gamma(\{\alpha_j\})/\partial\alpha_k = 0, \qquad k = 1\div 3, \tag{11}$$

with

$$S_\gamma(\{\alpha_j\}) = \ln\mathcal{Z}(\{\alpha_j\}) - \alpha_1 N - \alpha_2 Z + \alpha_3 U + \ln\Gamma(\{\alpha_j\},\epsilon_\gamma). \tag{12}$$

Next it is assumed that the dependence of the function s_λ on the saddle point parameters $\{\alpha_j\}$ is more smooth as that of the partition function $\mathcal{Z}(\{\alpha_j\})$, namely,

$$|\ \partial^n \ln s_\lambda/\partial^n\alpha_j\ | \ll |\ \partial^n \ln\mathcal{Z}/\partial^n\alpha_j\ |, \quad n = 1,2. \tag{13}$$

This assumption is in agreement with many investigations of the linear response function properties in medium and heavy heated nuclei (see, for example Refs. [27, 28, 35]. One finally obtains [1)] for the average radiative width $\bar{\Gamma}_\lambda(\epsilon_\gamma)$:

$$\bar{\Gamma}_\lambda(\epsilon_\gamma) = \left(\frac{\epsilon_\gamma}{\pi\hbar c}\right)^2 \sigma_\lambda(\epsilon_\gamma, T_f) \frac{\Omega(U-\epsilon_\gamma, Z, N)}{\Omega(U, Z, N)}, \tag{14}$$

where

$$\sigma_\lambda(\epsilon_\gamma, T_f) = \left(\frac{\pi\hbar c}{\epsilon_\gamma}\right)^2 s_\lambda(T_f, \epsilon_\gamma), \quad s_\lambda(T_f, \epsilon_\gamma) \equiv -\frac{d_\lambda(\epsilon_\gamma)}{\pi} \frac{Im\chi_\lambda(\omega, T_f)}{1-\exp(-\epsilon_\gamma/T_f)}. \tag{15}$$

Here, for simplicity, the designations a dependence of the functions s and χ on the parameters α_1 and α_2 is not indicated in Eq.(14) and below. The quantity $\Omega(U_f, Z, N)$ is the total density of the final states with the energy $U_f \equiv U - \epsilon_\gamma$ and the temperature $T_f \equiv \beta$,

$$\Omega(U_f, Z, N) = \exp[S_f(\{\alpha_j\})]/(2\pi)^2 \mid \det[[a_{kl}] \mid^{1/2}, \tag{16}$$

where $\det[a_{kl}]$ is the determinant of the matrix with the elements

$$a_{kl} = \partial^2 S_f / \partial\alpha_k \partial\alpha_l, \qquad k, l = 1 \div 3. \tag{17}$$

The parameters α_1, α_2 and $\alpha_3 \equiv 1/\beta \equiv 1/T_f$ are the solutions of equations of the thermodynamical state in final nucleus, i.e. they are the solutions of the Eq. (11) with the entropy of final states

$$S_f(\{\alpha_j\}) \equiv S_\gamma(\{\alpha_j\}) - \ln\Gamma(\{\alpha_j\}, \epsilon_\gamma) = \ln\mathcal{Z}(\{\alpha_j\}) - \alpha_1 N - \alpha_2 Z + \alpha_3 U_f$$

instead of the function S_γ.

The relation (14) is the same one as those given by detailed balance principle [4] with the photoabsorption cross-section $\sigma_\lambda(\epsilon_\gamma, T_f)$ given by Eq.(15). It follows from Eq.(14) and (7), (9) that the rate of the γ- transitions between excited states depends mainly on thermal fluctuations of the multipole moments in the final states.

General form of the $\sigma_\lambda(\epsilon_\gamma, T)$ coincides with that one from Refs. [26] - [28], [37, 38] obtained by making use of the averaging over the canonical ensemble with a constant temperature T.

The emission and absorption processes for γ-rays are generally connected with different radiative strengths [1, 14]. The gamma- decay (downward) strength function $\overleftarrow{f}_{E\lambda}$ determines the γ- emission of heated nuclei. It is associated with the average radiative widths $\bar{\Gamma}_\lambda(\epsilon_\gamma)$. The photoexcitation (upward) strength function $\overrightarrow{f}_{E\lambda}$ is connected with photoabsorption

[1)] Note that the expression for the average gamma width, with use of the microcanonical distribution and an assumption on a weak dependence of the width on ϵ_γ, was first considered in [36]. In this case the average radiative width is equal to $\bar{\Gamma}_\lambda(\epsilon_\gamma) = -d_\lambda(\epsilon_\gamma)/Im\chi_\lambda(\omega, T)/\pi$.

cross-section at fixed temperature T. For the dipole transitions these functions have the form

$$\overleftarrow{f}_{E1}(\epsilon_\gamma, T) \equiv \frac{\bar{\Gamma}_{\lambda=1}(\epsilon_\gamma)}{3\epsilon_\gamma^3} \frac{\Omega(U, Z, N)}{\Omega(U-\epsilon_\gamma, Z, N)} = \mathcal{F}(\epsilon_\gamma, T_f) \tag{18}$$

and

$$\overrightarrow{f}_{E1}(\epsilon_\gamma, T) \equiv \frac{\sigma_{\lambda=1}(\epsilon_\gamma, T)}{3\epsilon_\gamma(\pi\hbar c)^2} = \mathcal{F}(\epsilon_\gamma, T). \tag{19}$$

Here, spectral function $\mathcal{F}(\epsilon_\gamma, \mathcal{T})$ is given by

$$\mathcal{F}(\epsilon_\gamma, \mathcal{T}) \equiv \frac{s_{\lambda=1}(\mathcal{T}, \epsilon_\gamma)}{3\epsilon_\gamma^3} = -2e^2 \frac{NZ}{A} \left(\frac{2}{3\hbar c}\right)^3 \mathcal{L}(\epsilon_\gamma, \mathcal{T}) Im\chi^{(-)}(\omega, \mathcal{T}) \tag{20}$$

$$\mathcal{L}(\epsilon_\gamma, \mathcal{T}) \equiv 1/\left[1 - \exp(-\epsilon_\gamma/\mathcal{T})\right], \tag{21}$$

where $\chi^{(-)}(\omega, \mathcal{T}) = Sp(r\sum_\mu Y_{1\mu}^*(\hat{r})\delta n^{(-)})/q_\omega(t)$ is the response function of the heated nuclei to the field $q_\omega(t) r\sum_\mu Y_{1\mu}(\hat{r})$ and $\delta n^{(-)}(t) = \delta n_p(t) - \delta n_n(t)$ is the variation of the isovector single-particle density matrix. In the case of the spherical nuclei, we have $\chi^{(-)}(\omega, \mathcal{T}) = 3Sp(rY_{10}(\hat{r})\delta n^{(-)})/q_\omega(t)$ with the isovector density perturbation $\delta n^{(-)}(t)$ induced by the dipole field $q_\omega(t) rY_{10}(\hat{r})$.

Note that the γ- decay strength function depends on temperature T_f of the final states. This temperature is a function of the γ- ray energy in contrast to the initial states temperature T.

In the case of cold nuclei the radiative strength functions is also connected with the response function by Eqs.(18)-(20) but with factor $\mathcal{L} \equiv 1$. The scaling factor $\mathcal{L}(\epsilon_\gamma, \mathcal{T})$, (21), defines the enhancement of magnitude of the radiative strength functions in heated nuclei with temperature $\mathcal{T}$ as compared to the cold nuclei. This factor can be interpreted as average number of the 1p-1h excited states in heated system placed in an external field with energy $\hbar\omega$,

$$\Delta N_{1p-1h}(\omega, \mathcal{T}) \equiv \frac{1}{\hbar\omega} \int_0^{+\infty} \int_0^{+\infty} d\epsilon_1 d\epsilon_2 n(\epsilon_1)(1 - n(\epsilon_2))\delta(\epsilon_1 - \epsilon_2 + \hbar\omega) = \tag{22}$$

$$= \frac{1}{\hbar\omega} \int_0^{+\infty} d\epsilon_1 n(\epsilon_1)(1 - n(\epsilon_1 + \hbar\omega)) = 1/\left[1 - \exp(-\hbar\omega/\mathcal{T})\right],$$

where $n(\epsilon) = 1/[1 - \exp((\epsilon - \mu)/\mathcal{T})]$ is the Fermi distribution function for occupation of the single-particle states.

In order to get a simple closed-form expression for the response function, one assums as usual that gamma-decay is determined by the collective motion mode which excited in the associated photoabsorption process. Due to this the $E1$ transitions are considered as corresponding to the giant dipole excitations. Next the hydrodynamic model with damping ([39]) is applied for description of the collective motion of the neutrons against the protons which corresponds to the GDR in the classical picture. This approach is an extension of the Steinwedel- Jensen (SJ) model and provides a simple description of the GDR

excitation simultaneously with its damping. In common with the other classical hydrodynamics models SJ model with damping corresponds to the semiclassical description of the Fermi systems by means of the Landau-Vlasov kinetic equation with truncation of the Fermi sphere distortion by the layers of monopole and dipole multipolarities only [40]. Note that the SJ model describes volume oscillations of the transition density and these oscillations are almost unaffected by the dynamical distortion of the Fermi surface with multipolarities $l > 1$ [41]. The SJ mode plays most important role in heavy nuclei [42].

We make use of the expression for the induced dipole moment within the extended SJ model from \$14.4 of Ref.[39] and combine it with the relation for classical absorption cross-section and Eqs.(15), (20). Then we get the spectral function $\mathcal{F}(\epsilon_\gamma, \mathcal{T})$, Eqs.(20), in the form

$$\mathcal{F}(\epsilon_\gamma, \mathcal{T}) \equiv 8.674 \cdot 10^{-7} \frac{NZ}{A} \alpha_0 \beta_0^2 \frac{Y(z)}{1 - \exp(-\epsilon_\gamma/\mathcal{T})}, \quad MeV^{-3}, \tag{23}$$

where

$$Y(z) = Im \left\{ \frac{j_2(z)}{z j_1(z) - z^2 j_2(z)} \right\} = Im \left\{ \frac{1}{z^2} \left[\frac{\tan(z) - z}{\varphi(z)} - 1 \right] \right\} = \tag{24}$$

$$= \frac{A}{NZ\beta_0^2} \sum_{n \geq 1} f_n \frac{\epsilon_\gamma \Gamma}{(\epsilon_\gamma^2 - \epsilon_n^2)^2 + (\Gamma \epsilon_\gamma)^2}.$$

Here, $\epsilon_n = z_n/\beta_0$ and $f_n = (NZ/A)2/(z_n^2 - 2)$ are the energy and classical oscillator strength of the n - resonance, respectively; z_n are solutions of the equation $\varphi(z) \equiv (z^2 - 2)\tan z + 2z = 0$;

$$z = z(\epsilon_\gamma, \mathcal{T}) = \pm\beta_0 \left[\frac{0.5\epsilon_\gamma}{\widetilde{\epsilon}_\gamma} \right]^{1/2} [\widetilde{\epsilon}_\gamma + i\Gamma], \quad \widetilde{\epsilon}_\gamma = \epsilon_\gamma + \sqrt{\epsilon_\gamma^2 + \Gamma^2}, \tag{25}$$

and $\alpha_0 = 4\pi e^2 \hbar/(mc) = 0.305$; $\beta_0 = R_0/\hbar u$; $u = (4b_{vol}/m)(ZN/A^2)$ is the isovector sound velocity with the volume symmetry energy coefficient b_{vol} entering the semi-empirical mass formula; $j_n(z)$ are the spherical Bessel functions.

The quantity Γ in Eqs.(24) and (25) is damping width of the isovector velocity $\mathbf{v} = \mathbf{v}_p - \mathbf{v}_n$, where $\mathbf{v}_p$, $\mathbf{v}_n$ are velocities of the proton and neutron fluids, respectively. It determines the reduced friction force $\mathbf{v}\Gamma$ in the equation for isovector velocity, Eq. (14.60) from Ref.[39]. It can be seen that this term corresponds to the expression

$$\mathbf{v}\Gamma \equiv 2\hbar \int d\mathbf{p} (\mathbf{p}/m) J(\mathbf{p}, \mathbf{r}, t)/(2\pi\hbar)^3 \tag{26}$$

in semiclassical picture given by Landau-Vlasov equation with a source term $J(\mathbf{p}, \mathbf{r}, t)$ for relaxation processes [43, 44]. The source term is taken as the sum of two components [43, 44], $J = J_c + J_s$: the first one, J_c, is the isovector collision integral with retardation (memory) effects and the second one, J_c, is connected with fragmantation contribution to the damping width (isovector one - body relaxation). The latter component is described within the framework of the relaxation time approximation with the relaxation time τ_s different

from infinity only in the distorted layer of the Fermi surface with dipole multipolarity. The expression for damping width is obtained by the use of relation (26) and the expression for isovector collision integral from [44]. The width is the energy-dependent one and has the following form [2)]

$$\Gamma \equiv \Gamma(\epsilon_\gamma, T) = \Gamma_c(\epsilon_\gamma, T) + \Gamma_s, \qquad \Gamma_c(\epsilon_\gamma, T) = (m^*/m)\hbar/\tau_c(\epsilon_\gamma, T), \tag{27}$$

$$\Gamma_s \equiv (m^*/m)\hbar/\tau_s = (m^*/m)k_s(\epsilon_\gamma)\Gamma_w, \qquad \Gamma_w = \hbar\bar{v}/R. \tag{28}$$

Here, Γ_c and Γ_s are the collisional and one-body contributions to the total width, respectively. The quantity m^* is an effective mass of nucleon; we will use $m^* = m$. The quantities R and $\bar{v} = 3v_F/4$ are the nuclear radius and average velocity of the nucleon, respectively; v_F is the Fermi velocity.

The quantity $\tau_c(\epsilon_\gamma, T)$ is the collisional relaxation time for the isovector dipole distortion of the Fermi surface. It is associated with two-body collisions in the heated nucleus which is placed in the electric field with the frequency $\omega = \epsilon_\gamma/\hbar$. For the isotropic collision probabilities it is given by [43, 44]

$$\frac{\hbar}{\tau_c(\epsilon_\gamma, T)} = \frac{T^2}{\alpha}\left[1 + (\epsilon_\gamma/2\pi T)^2\right]. \tag{29}$$

The dependence of the relaxation time τ_c on the energy ϵ_γ results from memory effects in the collision integral and follows Landau's prescription [45, 47, 48, 49]. The temperature dependence arises from the smeared out behavior of the equilibrium distribution function near the Fermi momentum in the heated nuclei.

The quantity α in (29) is defined by the magnitude of the in-medium neutron-proton cross section $\sigma(np)$ near the Fermi surface

$$\alpha = \frac{const}{\sigma(np)}, \quad const = \frac{9\hbar^2}{16m^*} = 23.514, \;\; \alpha \; in \; MeV, \; \sigma(np) \; in \; fm^2, \tag{30}$$

The magnitude of the in-media cross section $\sigma(np)$ is usually taken proportional to a value of the free space cross section $\sigma_{free}(np)$ with a factor F,

$$\sigma(np) = F \cdot \sigma_{free}(np), \tag{31}$$

then the parameter α can be rewritten in the form

$$\alpha = \alpha_{free}/F = 4.7/F, \quad \alpha_{free} \equiv 23.514/\sigma_{free}(np) = 4.7, \tag{32}$$

when the value $\sigma_{free}(np) = 5 \; fm^2$ is adopted in line with Refs. [43, 48, 50, 51].

[2)] Here we do not use a normalization of the damping width to the value which corresponds to the zero-sound magnitude for the collisional width in infinite - matter with arbitrary multipolarities of the Fermi sphere distortion [43, 45, 46].

The quantities α and F determine two-body contribution B_c to the damping width of the GDR at zero temperature and the thermal relaxation time $\tau(T)$ for nuclear viscosity [52] in heated nuclei:

$$B_c \equiv \Gamma_c(\epsilon_\gamma = E_r, T = 0)/\Gamma_r = q/\alpha = F \cdot q/\alpha_{free}, \quad q = E_r^2/(\Gamma_r 4\pi^2),$$
$$\tau(T)/\hbar = \alpha \cdot b \cdot T^2, \quad b = (5/6)\sigma(pn)/\bar{\sigma} \approx 0.833\sigma_{free}(pn)/\bar{\sigma}_{free} \simeq 1.11, \tag{33}$$

where the E_r and $\Gamma_r \equiv \Gamma(\epsilon_\gamma = E_r, T = 0)$ are respectively the GDR energy and width at zero temperature; $\bar{\sigma} = [\sigma(pp) + \sigma(nn) + 2\sigma(pn)]/4$ is the in-media spin-isospin averaged nucleon-nucleon cross section near the Fermi surface; $\bar{\sigma}_{free} = 3.75fm^2$ free averaged cross section.

The values of the B_c should be located in the interval from 0 to 1. This condition determines the limiting values of α and F,

$$\alpha \geq \alpha_{min} \equiv q, \quad F \leq F_{max} \equiv \alpha_{free}/q = \alpha_{free}/\alpha_{min}. \tag{34}$$

The isovector one-body relaxation width Γ_s in (28) is taken to be similar to the wall formula expression Γ_w [30, 31, 42] but scaled with an energy-dependent coefficient $k_s(\epsilon_\gamma)$[43, 44, 53, 54]. The quantal calculations within framework of a simplified RPA[53] show significant reduction of the one-body width in comparison with the wall value,in particular $k_s \approx 0.1$ in the range where collective phonon energy exceeds the nuclear binding energy and $k_s \approx 0.7$ if collective phonon energy is negligibly small. The value $k_s = 0.62$ was adopted in Ref.[54].

The spectral function $\mathcal{F}$ given by Eqs. (23), (24) can be written in more convinient form

$$\mathcal{F}(\epsilon_\gamma, \mathcal{T}) = 8.674 \cdot 10^{-8} \frac{\sigma_r \Gamma_r}{1 - \exp(-\epsilon_\gamma/\mathcal{T})} \sum_{n=1}^{K} w_n \frac{\epsilon_\gamma \Gamma(\epsilon_\gamma, \mathcal{T})}{(\epsilon_\gamma^2 - \epsilon_n^2)^2 + (\Gamma(\epsilon_\gamma, \mathcal{T})\epsilon_\gamma)^2}. \tag{35}$$

Here, $w_n \equiv f_n/f_1 = (z_1^2 - 2)/(z_n^2 - 2)$; $K \to \infty$ and σ_r is the peak value of the photoabsorption cross-section

$$\sigma_r = 10.0\alpha_0 f_{n=1}/\Gamma_r \equiv 8.4(NZ/A)\alpha_0/\Gamma_r = 0.5\pi\sigma_{TRK}/\Gamma_r, \qquad mb, \tag{36}$$

where $\sigma_{TRK} \equiv 60NZ/A$ is the classical sum rule in $Mev \cdot mb$.

The first term in expansion (35) corresponds to the excitation of the GDR with the energy $E_r = \epsilon_{n=1}$ and therefore the quantities β_0, $\epsilon_{n>1}$ can be defined in the term of the GDR energy as

$$\beta_0 = z_{n=1}/E_r, \qquad \epsilon_n = x_n \cdot E_r, \quad x_n \equiv z_n/z_1, \quad z_1 = 2.08. \tag{37}$$

The values of the parameters q_n and x_n at $n \leq 4$ are given in Table 1.

Table 1: Values of parameters w_n and x_n.

n	1	2	3	4
w_n	1	0.070	0.028	0.015
x_n	1	2.86	4.42	5.97

The imaginary part of the dipole response function $\chi_{\lambda=1}$ associated with the Eq.(35) exhibits the resonance behaviour, in which the individual resonances have a Lorentzian shape with energy-dependent width. In the cold nuclei the first term of the expression (35) for the $Im\chi_{\lambda=1}$ was obtained within the random -phase approximation [55]. This first term of (35) is also in close agreement with the imaginary part of the response function of the heated Fermi - liquid drop on an external pressure, when approximation of the dissipative nuclear fluid dynamics is used for description of the system [46].

The γ- decay and photoexcitation dipole strength functions, (18),(19), have the same temperature-dependent limiting value for vanishing gamma-ray energy and it is equal to

$$\overleftarrow{f}_{E1}(\epsilon_\gamma = 0, T_f \equiv T) = \overrightarrow{f}_{E1}(\epsilon_\gamma = 0, T) =$$

$$= 8.674 \cdot 10^{-8} q_{K\to\infty} \sigma_r \Gamma_r T\Gamma(\epsilon_\gamma = 0, T)/E_r^4, \tag{38}$$

where $q_K \equiv \sum_{n=1}^{K} q_n/x_n^4$ and $q_{K\to\infty} \equiv (4/175)z_1^4/(z_1^2-2)$. All value of the sum $q_{K\to\infty} = 1.008656$ ($z_1 = 2.0815$) is practically contained in the first term $q_{K=1} = 1$.

TESTING OF THE CLOSED-FORM MODELS FOR CALCULATIONS OF E1 STRENGTH FUNCTIONS

Here, the calculations of the $E1$ radiative strength functions are compared within the framework of the SLO, EGLO models and the approach described in Sect.II. For not very high excitation energies the main contribution to the spectral function $\mathcal{F}$ results from the first term of the Eq.(35). Therefore, in what follows we use this approximation, and the expression (35) with $K = 1$ is referred to as the thermodynamic pole approximation [56] (TPA model), $\mathcal{F} \equiv \mathcal{F}_{TPA}$,

$$\mathcal{F}_{TPA}(\epsilon_\gamma, \mathcal{T}) = 8.674 \cdot 10^{-8} \frac{\sigma_r \Gamma_r}{1 - \exp(-\epsilon_\gamma/\mathcal{T})} \frac{\epsilon_\gamma \Gamma(\epsilon_\gamma, \mathcal{T})}{(\epsilon_\gamma^2 - E_r^2)^2 + (\Gamma(\epsilon_\gamma, \mathcal{T})\epsilon_\gamma)^2}. \tag{39}$$

The SLO spectral function, $\mathcal{F} \equiv \mathcal{F}_{SLO}$, has the Lorentzian form but with the energy independent width Γ_r rather than $\Gamma(\epsilon_\gamma, \mathcal{T})$,

$$\mathcal{F}_{SLO}(\epsilon_\gamma, \mathcal{T}) = 8.674 \cdot 10^{-8} \sigma_r \Gamma_r \frac{\epsilon_\gamma \Gamma_r}{(\epsilon_\gamma^2 - E_r^2)^2 + (\Gamma_r \epsilon_\gamma)^2}. \tag{40}$$

The EGLO dipole spectral function is given by [24, 25], $\mathcal{F} \equiv \mathcal{F}_{EGLO}$,

$$\mathcal{F}_{EGLO}(\epsilon_\gamma, \mathcal{T}) = 8.674 \cdot 10^{-8} \sigma_r \Gamma_r \left[\frac{\epsilon_\gamma \Gamma_k(\epsilon_\gamma, \mathcal{T})}{(\epsilon_\gamma^2 - E_r^2)^2 + (\epsilon_\gamma \Gamma_k(\epsilon_\gamma, \mathcal{T}))^2} + 0.7 \frac{\Gamma_k(\epsilon_\gamma = 0, \mathcal{T})}{E_r^3} \right], \quad (41)$$

where the energy-dependent width $\Gamma_k(\epsilon_\gamma, \mathcal{T})$ is equal to

$$\Gamma_k(\epsilon_\gamma, \mathcal{T}) = \left[\kappa_0(A) + (1 - \kappa_0(A)) \frac{\epsilon_\gamma - \epsilon_0}{E_r - \epsilon_0} \right] \cdot \left(\epsilon_\gamma^2 + (2\pi\mathcal{T})^2 \right) \frac{\Gamma_r}{E_r^2}, \quad (42)$$

where $\kappa_0(A)$ is the empirical factor; $\epsilon_0 = 4.5 MeV$. For the case $\kappa_0(A) = 1$, the quantity Γ_k corresponds to the expression for the collisional damping width in the infinite matter.

The values $\kappa_0(A)$ are mainly obtained by fitting of the low energy experimental data and they depend on the models used for calculations of the temperature and level density. The two expressions for quantity $\kappa_0(A)$ are recommended in [25]

$$\kappa_0(A) = \begin{cases} 1, & A < 148, \\ 1 + 0.09(A - 148)^2 \exp\left(-0.18(A - 148)\right), & A \geq 148, \end{cases} \quad (43)$$

when the backshifted Fermi gas model [57] (BSFG) is taken for level densities, and

$$\kappa_0(A) = \begin{cases} 1.5, & A < 145, \\ 1.5 + 0.131(A - 145)^2 \exp\left(-0.154(A - 145)\right), & A \geq 145, \end{cases} \quad (44)$$

for level density from [58].

Below the backshifted Fermi gas model[57] is adopted and the Eq.(43) for $\kappa_0(A)$ is used. The equations for the temperatures T, T_f have the following form

$$T = \frac{1 + \sqrt{1 + 4a(U - \Delta)}}{2a}, \quad (45)$$

$$T_f = \frac{1 + \sqrt{1 + 4a(U - \epsilon_\gamma - \Delta)}}{2a} = \frac{1 + \sqrt{1 + 4a(aT^2 - T) - 4a\epsilon_\gamma}}{2a},$$

where Δ the energy shift parameter and a the level density parameter. The values of the a and Δ are taken from the data file *beijing_bs1.dat* at the rigid-body value for moment inertia (see, the RIPL Handbook[25], Ch.5), and from the global fitting in[59], namely,

$$a = 0.21 A^{0.87}, \quad MeV^{-1}, \quad \Delta = -6.6 A^{-0.32} + \chi \cdot 12 A^{-0.5}, \quad MeV, \quad (46)$$

when data in Ref.[25] are absent. Here, $\chi = 0$, 1 and 2 for odd-odd, odd-even(even-odd) and even-even nuclides, respectively.

For very small temperature T and with negative values of Δ the BSFG model can lead to negative values of the initial excitation energy $U \equiv aT^2 - T + \Delta$. In this case usual Fermi-gas model is used for calculation of the energy, $U = aT^2$.

The values of the GDR energy, E_r, and width, Γ_r, and the peak of the $E1$ absorption cross-section, σ_r, are considered as the temperature- independent and taken from photonuclear data file *beijing_gdr.dat*[25] (when the data exist) or from the global systematics at zero temperature. In the last case they equal

$$E_r = 31.2A^{-1/3} + 20.6A^{-1/6},\ \Gamma_r = 0.026E_r^{1.91},\ \sigma_r = 1.2 \cdot 120NZ/(A\pi\Gamma_r), \tag{47}$$

for spherical nuclei and

$$\begin{gathered} E_{r,1} = E_r/(1 + 2\beta/3), \qquad E_{r,2} = E_r/(1 - \beta/3), \\ \Gamma_{r,1} = 0.026E_{r,1}^{1.91}, \qquad \Gamma_{r,2} = 0.026E_{r,2}^{1.91}, \\ \sigma_{r,1} = \sigma_r/3, \qquad \sigma_{r,2} = 2\sigma_r/3, \end{gathered} \tag{48}$$

for deformed nuclei, where β is the quadrupole deformation parameter. All deformed nuclei are considered as the axially symmetric spheroids with the effective quadrupole deformation parameters β. For every nucleus the quantity β is founded as an effective quadrupole deformation parameter which gives the same value of quadrupole moment (Q) as it is in the case when the general expression for the Q ([60], Eq.6.53) is used allowing for the deformations of multipolarities $L = 2, 4, 6$ with parameters β_2, β_4 and β_6, respectively. The values of the last parameters were taken from *Moller.dat* file for nuclear ground-state masses and deformations from RIPL[25], Ch.1, (see also [61]). The quantity of β is evaluated by the relation

$$\beta = \beta_2 + 0.36\beta_2^2 + 0.967\beta_2\beta_4 + 0.328\beta_4^2 + 0.023\beta_2^3 - 0.021\beta_2^4 + 0.499\beta_2^2\beta_4. \tag{49}$$

For axially deformed nuclei the $E1$ strengths (18) and (19) are the sum of two spectral function $\mathcal{F}$ with the parameters $E_{r,1}$, $\Gamma_{r,1}$, $\sigma_{r,1}$ and $E_{r,2}$, $\Gamma_{r,2}$, $\sigma_{r,2}$, respectively.

The two approaches are used for the scaling coefficient $k_s(\epsilon_\gamma)$ in Eq.(28) for one-body isovector width Γ_s:

1) the energy-independent value

$$k_s(\epsilon_\gamma) \equiv k_s(\epsilon_\gamma = E_r) = (\Gamma_r - \Gamma_c(\epsilon_\gamma = E_r, T = 0))/\Gamma_w, \tag{50}$$

i.e., the quantity $k_s(E_r) \equiv k_s(\epsilon_\gamma = E_r)$ is obtained from fitting of the the GDR width at zero temperature and it defines the one-body contribution near the GDR resonance energy;

2) the energy-dependent value in a power approximation of the form

$$k_s(\epsilon_\gamma) = \begin{cases} k_s(E_r) + (k_s(0) - k_s(E_r))|(\epsilon_\gamma - E_r)/E_r|^n, & \epsilon_\gamma < 2E_r, \\ k_s(0), & \epsilon_\gamma \geq 2E_r, \end{cases} \tag{51}$$

where the quantity $k_s(0) \equiv k_s(\epsilon_\gamma = 0)$ defines the fragmentation width at zero energy.

Table 2: The optimal parameter sets at given n and the least-squares deviations per one degree of freedom, χ^2_{TPA}, for TPA model.

n	$k_s(0)$	F	B_c	χ^2_{TPA}
0	$k_s(E_r)$	2.5	0.58	10.5
0.5	0.3	1.5	0.35	9.4
1	0.3	2.0	0.46	10.2
3	0.1	4.0	0.93	15.2
3	0.3	2.0	0.46	12.6
3	0.7	3.0	0.7	10.1
3	1.0	4.0	0.93	13.8

The sets of optimal parameters for calculations of the TPA response function widths at fixed degree n of the power approximation from (51) are shown in Tabl.2. The last column in the Table 2 contains the values of the least-squares deviations per one degree of freedom of the TPA calculations from experimental E1 strength functions data in (n,γ) reaction from *Kopecky.dat* file of the RIPL-handbook([25]),

$$\chi^2 = \sum_{i=1}^{i_{max}=53} \left[(\overleftarrow{f}_{E1}(A_i) - fE1(A_i))/a[fE1(A_i)] \right]^2 .$$

Here, $fE1(A_i)$ and $a[fE1(A_i)]$ are respectively experimental average value of E1 strength and its uncertainty recommended for nucleus with mass number A_i corresponding to the i-th experimental value, $i_{max} = 53$. The model strength functions $\overleftarrow{f}_{E1}(A_i)$ were calculated at excitation energies and gamma-ray energies equal to mean energy of E1 transitions, $EgE1$, from the data file, $E(A_i) = \epsilon_\gamma(A_i) = EgE1(A_i)$.

The values of deviations χ^2_{TPA} are in most cases less than in the EGLO approach for which $\chi_{EGLO} = 13.8$. The magnitude of the least-square deviation is equal to $\chi^2_{SLO} = 50.6$, i.e. overall fitting experimental data from *Kopecky.dat* file by the TPA and EGLO models is better than within the SLO model.

The quantity B_c, (33), appears as more convenient than F in calculations of the α,

$$\alpha \equiv q/B_c = 4.7/F, \quad q = 0.02533 \cdot E_r^2/\Gamma_r, \tag{52}$$

determining two-body component of the width by Eqs.(27), (29). The reason is that maximal value of the F is changed from nucleus to nucleus as opposite to B_c, see Eqs.(33) and (34).

It should be noted that the damping component Γ_c given by the Eqs.(27), (29) with α from (32), (33), is two-body relaxation width only in some specific medium where multipolarity of the Fermi sphere distortion does not exceed dipole multipolarity and two-body collisions are isotropic ones with energy- independent cross-sections $\sigma = \sigma_{free}$. Therefore the parameters

B_c, (33), and F, (31), are respectively two-body contribution to width and proportionality factor of the in-medium cross-section to free-space magnitude in the specific medium and their values account for the difference between real system and specific medium too.

The dipole γ- decay strength functions $\overleftarrow{f}_{E1}$ considered as a function of mass number are shown in Fig.1. The experimental data taken from *Kopecky.dat* file of the RIPL-handbook([25]). Calculations were performed for nuclei from this data file (50 nuclei corresponding to (n,γ) reaction) and at excitation energies and gamma-ray energies are equal to mean energy of E1 transitions. These energies are rather close to the corresponding neutron binding energies. The different lines connect the values calculated within framework of given model. Hereafter the values $n = 0.5$, $k_s(0) = 0.3$, $B_c = 0.35$ and $n = 3$, $k_s(0) = 0.7$, $B_c = 0.7$ are used in TPA calculations. The values of index n are only indicated in the figure for short.

As it can be seen from this figure, for gamma-ray energies near neutron binding energies the calculations within the TPA model describe experimental data in somewhat better way for heavy nuclei with $A \gtrsim 150$ as compared with other approaches. The parameters $n = 3$, $k_s(0) = 0.7$ $B_c = 0.7$ can be recommended as more appropriate set in TPA calculations.

In Fig.2 the results of the calculations of the strength functions $\overleftarrow{f}_{E1}$ in ^{144}Nd with the initial excitations energy E which is equal to the neutron binding energy $B_n \approx 7.8\ MeV$ are shown. The experimental data are taken from Ref.[15].

The results obtained by EGLO and TPA approaches are almost the same at low energies $\epsilon_\gamma \lesssim 3MeV$. In this range the EGLO and TPA models describe experimental data much better than the SLO model and give a non-zero temperature-dependent limit of the strength function for vanishing gamma-ray energy, see Eq.(38). The calculations by TPA and SLO models at the energies $\epsilon_\gamma \gtrsim 5MeV$. lie more close to experimental data than within EGLO method.

Figure 3 demonstrates the dependence of the γ -decay TPA strength function on the initial excitation energy U. The E1 strength depends rather strongly on the energy U. It is usually named as a breakdown of Brink hypothesis [14]. This violation of Brink hypothesis is growing with increasing excitation energy. The difference of the $E1$ strength function values calculated at different U is increased with decreasing γ - energies and these deviations are more important for the γ - transitions with energies under or of the order of the nuclear temperature T.

In Figs.4, 5 the comparison is shown between different approaches in the case the photoabsorption strength function $\overrightarrow{f}_{E1}$, Eqs.(19), (39), (40) and (41) at different values of the temperature $T = 0.01, 2MeV$ of absorbing nucleus ^{144}Nd. The notations are the same as in Figs.2. The experimental data are taken from Ref.[15]. They correspond to (n, γ) reaction at $\epsilon_\gamma = 6 - 8MeV$ and were obtained from photoabsorption cross-section in the range $\epsilon_\gamma > 8MeV$.

The behaviour of the E1 strength functions calculated by the TPA method is almost in coincidence with SLO model in the vicinity of the GDR peak energy. It is mainly resulted from account of the one-body relaxation width Γ_s, (28), which is practically independent of the gamma-ray energy. Note that the SLO approach is probably the most appropriate

simple method for the estimation of the E1 photoabsorption strength for cold nuclei in the range of giant resonance peak energy. The strength function $\overrightarrow{f}_{E\lambda}$ depends only weakly on the temperature if a magnitude of the T is much smaller than the gamma-ray energy. The form of the strength is rather sensitive to the excitation energy of absorbing nucleus at low energies of the γ -rays.

CONCLUSIONS

A closed-form TPA approach is developed for average description of the E1 radiative strength functions. This method is not time consuming and is applicable for calculations of the statistical contribution to the dipole strengths for processes of the gamma-decay as well as photoabsorption with compound system formation. It has the following main features:

1. The general expression between radiative strength function and imaginary part of the temperature response function is used. This relationship is based on microcanonical ensemble for initial excited states and it is in line with a detailed balance principle.

2. The form of the temperature response function is taken within framework of the Steinwedel- Jensen hydrodynamic model with damping. The response function has the Lorentzian line shape (two for axially deformed nuclei) with width depending on γ- ray energy. The Landau-Vlasov kinetic approach with the monopole and dipole distortions of the Fermi sphere is employed to calculate the damping width which is proportional to friction coefficient of the isovector velocity of the relative motion of the protons over neutrons.

3. Description of damping in the TPA method is based on modern physical understanding of the relaxation processes in Fermi systems. The contributions to the Lorentzian width resulting from the interparticle collisions as well as fragmentation component caused by interaction of particles with time dependent self-consistent mean field are included. A method of independent source of relaxation is employed to account for all contributions to width. The energy dependence of the collisional contribution is arisen from memory effects in the collision integral.

4. The form of the E1 radiative strength function within framework of the TPA model is determined by both the Lorentzian shape of the response function with energy dependent width and an average number of the excited 1p-1h states at given γ-ray energy. Shell structure and pairing correlations are included in phenomenological way by use of the level density parameters allowing for these effects. The TPA approach is characterized by a non-zero limit of the E1 strength for vanishing gamma-ray energy. It gives the temperature-dependent form of the strength, i.e. leads to a breakdown of Brink hypothesis.

The comparison between calculations within TPA, EGLO and SLO models and experimental data showed that the TPA approach provides rather reliable method of a unified description of the γ - decay and photoabsorption strength functions in a relatively wide energy interval, ranging from zeroth gamma-ray energy to values above GDR peak energy. The TPA model will be useful for the prediction of the downward and upward radiative strength functions for cold and heated nuclei. The values $n = 3$, $k_s(0) = 0.7$ and $B_c = 0.7$ can be recommended as best suited set to calculations of the E1 strengths in medium and heavy

nuclei by the TPA model. It should be noted that a behaviour of the TPA strength functions is rather sensitive to the type of γ-ray energy dependence of scaling coefficient $k_s(\epsilon_\gamma)$ in Eq.(28) for one-body isovector width. The phenomenological approximations (50) and(51) are currently used. The further investigations of the fragmentation width are necessary to refine the form of the scaling coefficient.

The results obtained within this project were partly published in [44, 56], namely,

1) V.A.Plujko, Acta Phys.Pol. B30(1999)1383-1391.
Draft version: http: //xxx.lanl.gov/abs/nucl-th/9809010;

2) V.A.Plujko, Nucl.Phys. A649(1999)209c-213c.
Draft version: http: //xxx.lanl.gov/abs/nucl-th/9809012.

They also were reported on the following conferences

1) The topical Conference on Giant Resonances, Varenna (Como Lake) Villa Monastero, 1998,Italy. Book of abstracts.P.53,56;

2) Intern. Conf. Nucl. Phys. Close to the Barrier, The centennial of the discovery of Polonium and Radium, Warsaw University, Heavy Ion Laboratory, 30.06 - 4.07.1998, Warsaw,Poland. Abstracts.P.62,63;

3) International Conference on Nuclear Physics (49th Workshop on Nuclear Spectroscopy and and Nuclear Structure), 21-24 April 1999, Dubna. Russia. Book of abstracts.P.347,348;

4) Workshop on Collective excitations in Nuclei and other Finite Fermi systems, 21-24 June 1999, Dubna. Russia;

and were also presented on the RIKEN Symposium and workshop on Selected topics in nuclear collective excitations, March 20 - 24, 1999, Wako, Saitama, Japan. Abstracts.P.34,35.

As a part of the project, the modifications of the *Kopecky.dat* and *Kopecky.readme* files from Segment 6 of the RIPL Handbook [25] are made. The *Kopecky.dat* file containing experimental data base of E1 and M1 gamma-ray strength functions was converted into the computer readable version and passed to the IAEA.

The computer codes were created for the calculations and plotting of the E1 radiative strength functions versus mass number and gamma-energy by the SLO, EGLO and TPA models under MS-DOS (see Appendix 1) and Windows 3.1X/9X (see Appendix 2) operating systems. They were passed with full description to the IAEA. The codes are written in Fortran and Delphi programming languages. An option of visual comparison between the calculations and experimental data is included. Numerical data output in the computer readable form is done.

ACKNOWLEDGMENTS

Useful discussions and comments by Profs. A.V. Ignatyuk, P. Oblozinsky and M.G. Urin are greatfully acknowledged.

APPENDIX 1

GENERAL INFORMATION ON THE COMPUTER CODE fE1_vs_A.for
AND THEIR ASSOCIATED PROGRAM FILES

The fE1_vs_A.for is a FORTRAN code at DOS (MS Fortran 5.0 and above) (written by S.Ezhov and V.Plujko) for calculation of the E1 gamma-decay strength functions (fE1=f_gd(Eg,U)=f(A)) as a function of mass number A at fixed excitation energy U. A gamma-ray energy value is given by Eg= U*REDUCE. The calculations are performed for 50 nuclei from'Kopecky.dat' file (RIPL) which contains experimental data base of radiative strength functions.The recommended data for (n,gamma) reaction (Key Reac.=1 and 3) are used only. The radiative strengths are calculated within the framework of the TPA, EGLO and SLO models.

HOW TO WORK WITH THE fE1_vs_A

I. File 'fE1_vs_A.bat'file should be run. DOS file fE1_vs_A.BAT is batch file for running of the DOS program files fE1_vs_A.exe, GNUPLOT.exe for calculation and plotting E1 gamma-decay strength functions. The DOS program file fE1_vs_A.exe is used for calculation of the E1 gamma- decay strength functions versus mass number. This program file is obtained by running at the DOS of the Fortran code fE1_vs_A.for (MS Fortran 5.0 and above). The free GNUPLOT.EXE program is used for showing results on display. It has the following copyright and permission (see, file GNUPLOT.gih):

II. The regimes of the work should be set providing answers to the questions on display. There are the following settings:

1)

```
**************************************
*                                    *
*  Specify the representation form   *
*  of E1 strength function for output *
*  data in "RESULTS.DAT" file and    *
*  the data plotting:                *
*                                    *
*  1 - fE1                 (MeV^-3)  *
*  2 - fE1/(A^(2/3))       (MeV^-3)  *
*  3 - fE1/(A^(8/3)Eg^2)   (MeV^-5)  *
*                                    *
**************************************
```

2)

```
*****************************************************
*  Specify the values of the excitation            *
*  energies U:                                      *
*                                                   *
*  1- U = Eg from KOPECKY.DAT                       *
*  2- U =  neutron binding energies                 *
*          scaled by factor ENERCO                  *
*  3- U = COMENE (identical value for all nuclei)  *
*                                                   *
*****************************************************
```

a) If set 2

```
**********************************
*  Set scaling factor ENERCO     *
**********************************
```

b) If set 3

```
**********************************
*  Set a value of COMENE  (in MeV)  *
**********************************
```

3)

```
*********************************************
*                                           *
* Introduce value of IV = 1 - 2 determining *
* type of the parameters used for           *
* calculations of the relaxation width.     *
*                                           *
* IV=1 -> Calculations  at fixed two-body   *
*         contribution, Bc, to the GDR widths *
*         in cold nuclei.                   *
*                                           *
* IV=2 -> Calculations at given value       *
*         of the in-medium cross section,   *
* SIGMA_NP(in-medium)=SIGMA_NP(free)*F,     *
*  i.e.,                                    *
* WIDTH_{coll,in}=WIDTH_{coll,free}*F.      *
*                                           *
*********************************************
```

a) If set IV=1

```
*********************************************
*                                           *
* Setting of the Bc value which is two-body *
* contribution to the GDR width  at zero    *
* temperature (Bc is located between 0 and 1) *
*********************************************
```

a) If set IV=2

```
*********************************************
*     Choose value of F  between            *
*            0  and  ',g8.2,'*)             *
*********************************************
```

*) It is the maximal value of F for nuclei from KOPECKY.DAT file.

4)

```
*****************************************
*                                       *
* Setting of a gamma-ray energy value   *
* Eg in the form Eg= U*REDUCE by        *
* specifying of the value REDUCE        *
*                                       *
* Set value of REDUCE (from 0 to 1)     *
*                                       *
*****************************************
```

5) Choice of the scaling factor form for 1-body contribution

```
*************************************************
*                                               *
* Choose the form of the k_(s) which            *
* determines one-body contribution to           *
* to the damping width and set value KS:        *
*                                               *
* KS=1 -> k_(s) is independed of gamma-energy   *
* KS=2 -> k_(s)(Eg), power approximation        *
*                    with degree "n"            *
*                                               *
*************************************************
```

a) If set KS=1

k_(s)(0)=k_(s)(Eg=Er) and n=0

b) If set KS=2

```
*************************************************
*                                               *
*  Set of the k_(s)(0) value of the one-body    *
*  contribution to width at zero energy         *
*                                               *
*************************************************
*************************************************
*                                               *
*  Set of the n value of the degree for         *
*               k_(s)(Eg)                       *
*                                               *
*************************************************
```

III. To see results on the screen one should press 'Enter', when message 'Press enter' is appeared. The lines denoted as 'average.dat' correspond to the average values of reduced E1 strengths: 2.9e-9 (MeV^-3) for fE1/(A^(2/3)) and 4.2e-15 (MeV^-5) for fE1/(A^(8/3)Eg^2).

To exit from the program one should press two times 'q' and then 'Enter'.

The results of the calculations are located in output file'RESULTS.DAT'. The values of the least-squares deviations deviations per one freedom degree (chi2) of the calculations (f(A)) from experimental data also given in this file.

APPENDIX 2

GENERAL INFORMATION ON GRSF PROGRAM

The GRSF is the program file for Windows 3.1/9X (written by A.Mikulyak, scientific adviser V.Plujko) for calculation and plotting of the E1 radiative strength functions both for gamma-decay, f_gd(Eg,U), and for photoexcitation,f_ab(Eg,U), processes. The radiative strengths with gamma-energy Eg for the compound nucleus with initial excitation energy U (temperature Ti) are calculated within the framework of the TPA, EGLO and SLO models. The radiative strength functions are calculated as functions either of gamma-ray energy (f(Eg)) or mass number (f(A)). In the second case E1 strengths are calculated for 50 nuclei from 'Kopecky.dat' file (RIPL) which contains experimental data base of radiative strength functions. The recommended data for (n,gamma) reaction are used only.

MENU COMMANDS DESCRIPTION

FILE menu (contains common file management routines)

SUBMENUS

Load data file - Loading data file from the disk (Ctrl+O shortcut).

Close data file - Closing allready opened data file.

Save - Saving results on the disk (Ctrl+S shortcut).

Exit - Quit from GRSF.

ACTIONS menu (contains calculation and plotting routines)

SUBMENUS

Set parameters - Setting calculation parameters and type of the calculated strength functions.

Plot - Plotting calculations in the window (F9 shortcut).

Clear - Clearing plot window (F10 shortcut).

Select data for plot - Selection/unselection of the models, data and files which can be plotted in the window.

Calculate chi2 - Calculation of the least-squares deviations per one degree of freedom (chi2) of the calculations from experimental E1 strength functions data in (n,gamma) reaction from KOPECKY.DAT file (for f=f(A) mode only); corresponding toolbar button is "chi2" (Ctrl+F9 shortcut).

Calculate Bc - Calculation of the two-body contribution to the GDR width at zero temperature at given F; corresponding toolbar button is "Bc" (Ctrl+F10 shortcut).

OPTIONS menu (contains program options)

SUBMENUS

Set Data Libraries - Setting experimental (and other) data libraries (all the GRSf libraries initially located in the LIB subdirectory).

Frame Style - Selection style of the frame in the window.

Set Plot Style - Setting data color, line and point style. Defaults: colors TPA - red, SLO - green, EGLO - navy; lines without points; for '*.dat' files: colors - black; points without lines.

Show Hints - Toggling hints on/off; default - on

HELP menu (contains file with help)

SUBMENUS

Contents - Displayng main GRSF help file (F1 shortcut)

About - Showing program information

TOOLBAR description
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Toolbar buttons duplicate corresponding menu items. There are
hints for the each of the toolbar button.

PERFORMING BASIC OPERATIONS WITH GRSF

I. Setting parameters

To set parameters, click on the button "Set parameters"
(or "Actions / Set parameters" menu item. The form entitled
"Set parameters" will be displayed. Necessary options
on the first page should be selected.

1) Choose type of strength functions as functions of
   gamma-ray energy f(Eg) or mass number f(A);

2) Indicate type of used excitation parameters (initial
   temperature or excitation energy);

3) Set type of strength (gamma-decay or photoabsorption);

4) Set the values of the parameters Bc or F, which define
   collisional contribution to the width;

4) Set the values of the parameters k_(s)(0) = ks0 and n = Degree,
   which define scaling factor of one-body isovector component of
   the width (the value n=0 is set if Degree < 0).

After selection options on the first page the "Continue" button
should be pressed. New page will be displayed which depends on
strength function type (f=f(A) or f=f(Eg)). In the case of f=f(Eg)
you should enter necessary parameters in the corresponding edit
boxes (nuclide, level density and GDR parameters) and then press
"Ok" button. You can use parameters from data library (Ctrl+B key),
parametrization (Ctrl+P key) or given by manually (see hints for
shortcuts on this page). In the case when library is used, the
quadrupole deformation parameter 'beta' is automatically calculated
by

beta=3*(Er2-Er1)/(2*Er1+Er2).

In the case of f(A) calculations the values of the excitation energies should be selected only:

1) radiobutton U = EgE1 means that excitation energies are equal to gamma-ray energies from KOPECKY.DAT file;
2) radiobutton U = Bn means that excitation energies equal neutron binding energies.

II. Plotting

Plot style and frame attributes should be selected for plotting. For selection plot style it is necessary to click on the "Plot Style" button (or choose the "Options/Plot Style" menu item). The color, line and point style should be selected for each data. Setting by default is the following: colors TPA - red, SLO - green, EGLO - navy; lines without points; for .dat files: colors -black with points without lines. To set frame attributes it is needed to press button "Frame Style" (or choose "Options/Frame Style" menu item). Default frame attributes are the following: show legend, don't show X, Y grid lines; X axis range define automatically (f= f(Eg) -> 0 < Eg < Egmax = U; f = f(A) -> A = 0-250). To display calculated data it is needed to click "TPA", "EGLO", "SLO" buttons (or select "Actions/Select Data for Plot" menu item). Then you should click "Plot" button (or "Action/Plot" menu item or F9 key) and plot will be displayed. Press button "Clear plot" (or "Actions/Clear plot" menu item) if it's necessary to erase plot. Note, that after changing parameters or window resizing plot refresh itself.

III. Working with data files

To load data file it is necessary to click "Load data file" button (or set "File/load data file" menu item) and then needed data file in open dialogue window should be selected. To plot data files it is needed to click "Select data file for plot" button (or set "Actions/Select data for plot/Data files" menu item). The specified data file should be selected and then it will be displayed. To close data file menu item "File/Close data file" should be selected and the file be indicated.

IV. Saving of the results

To save results it is necessary to click "Save results to disk" button (or set "File/Save" menu item or Ctrl + S key). In the case of f=f(A) experimental data from KOPECKY.DAT will be saved together with the calculations. By default, the calculations are performed in 200 points.

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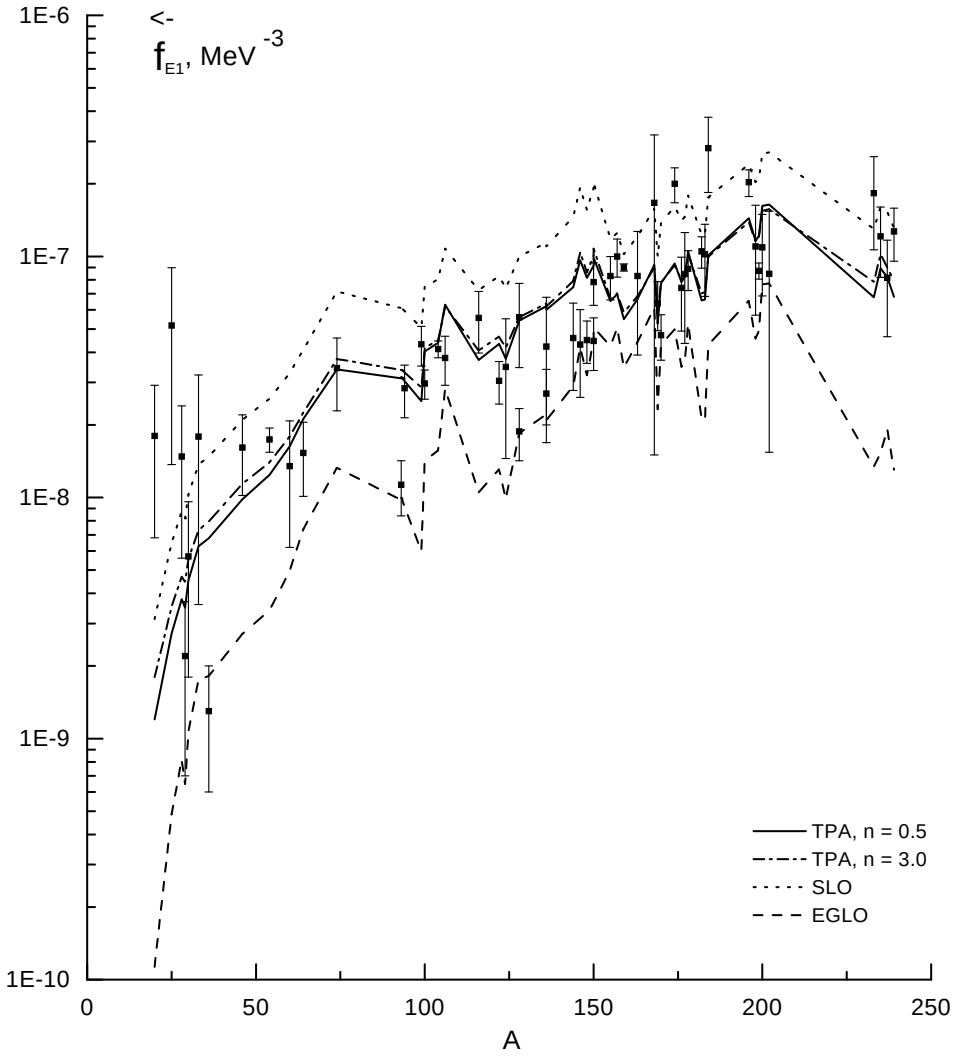

Fig. 1. The E1 gamma-decay strength functions versus mass number A.

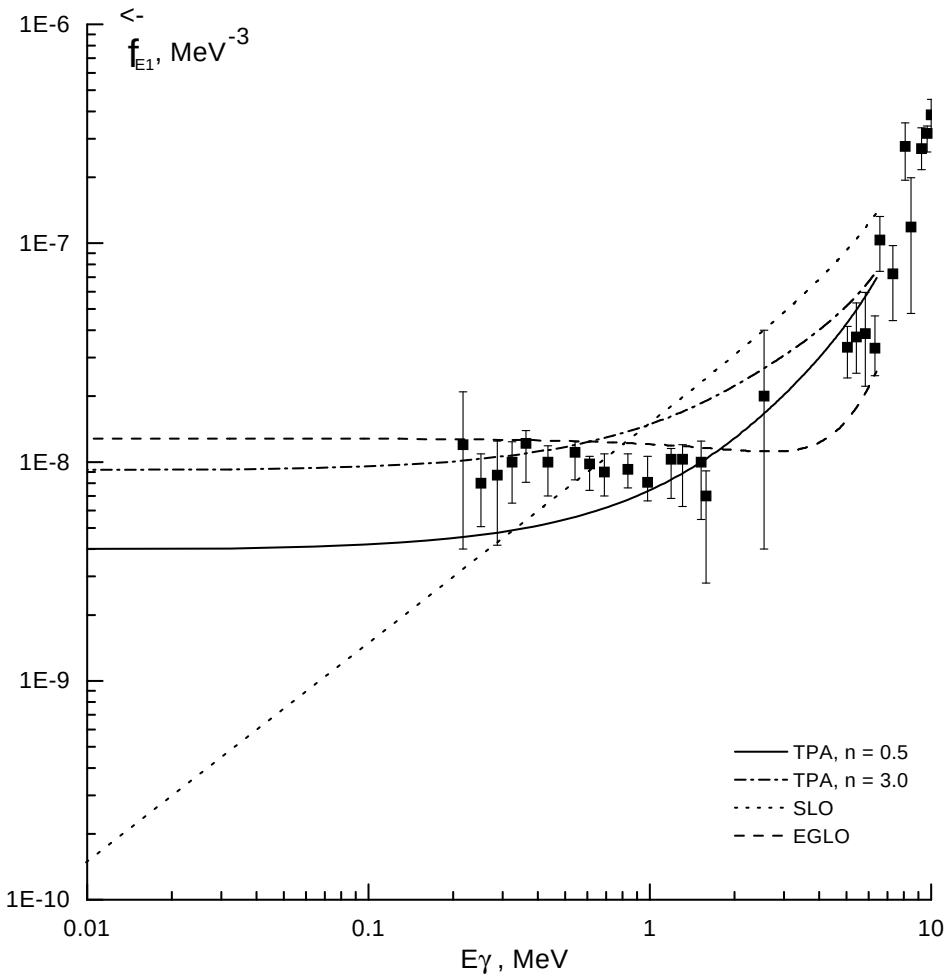

Fig. 2. The E1 gamma-decay strength functions
of Nd^{144} for U=Bn.

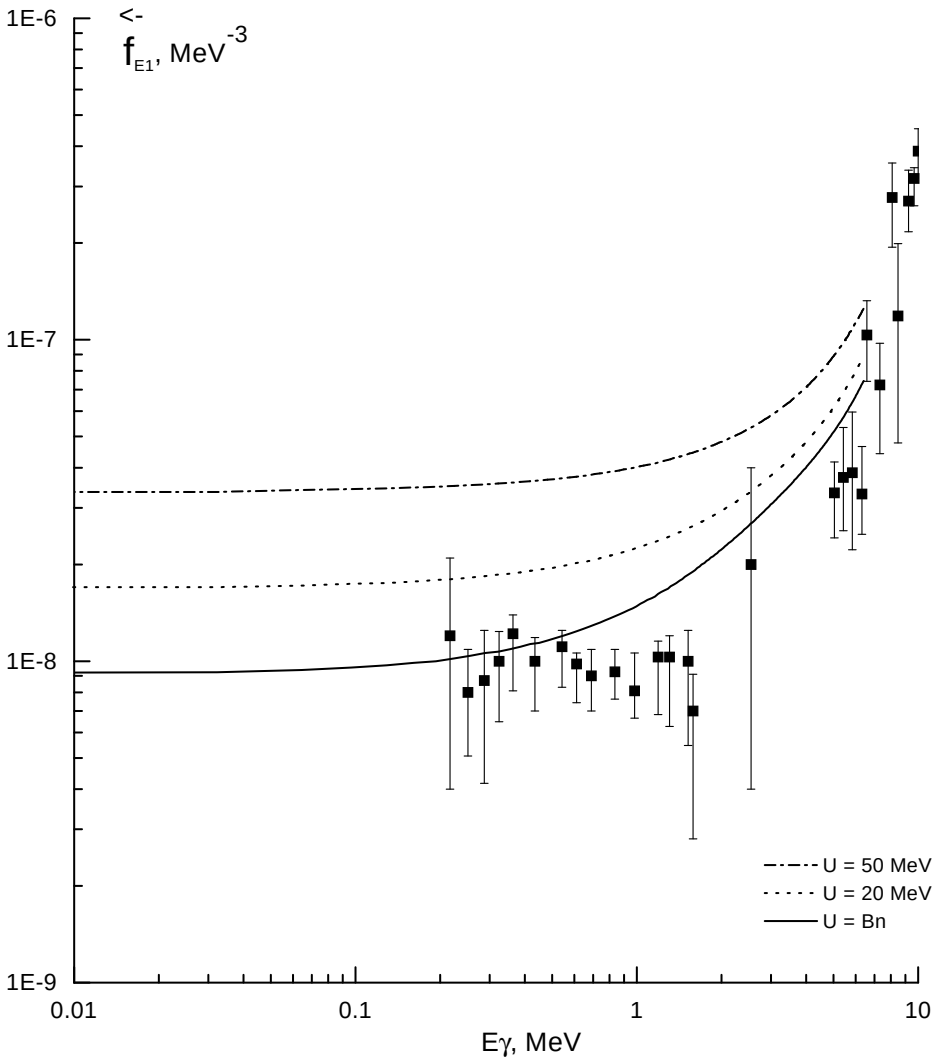

Fig. 3. The dependence of the gamma-decay strength functions at different excitation energies, n = 3.0.

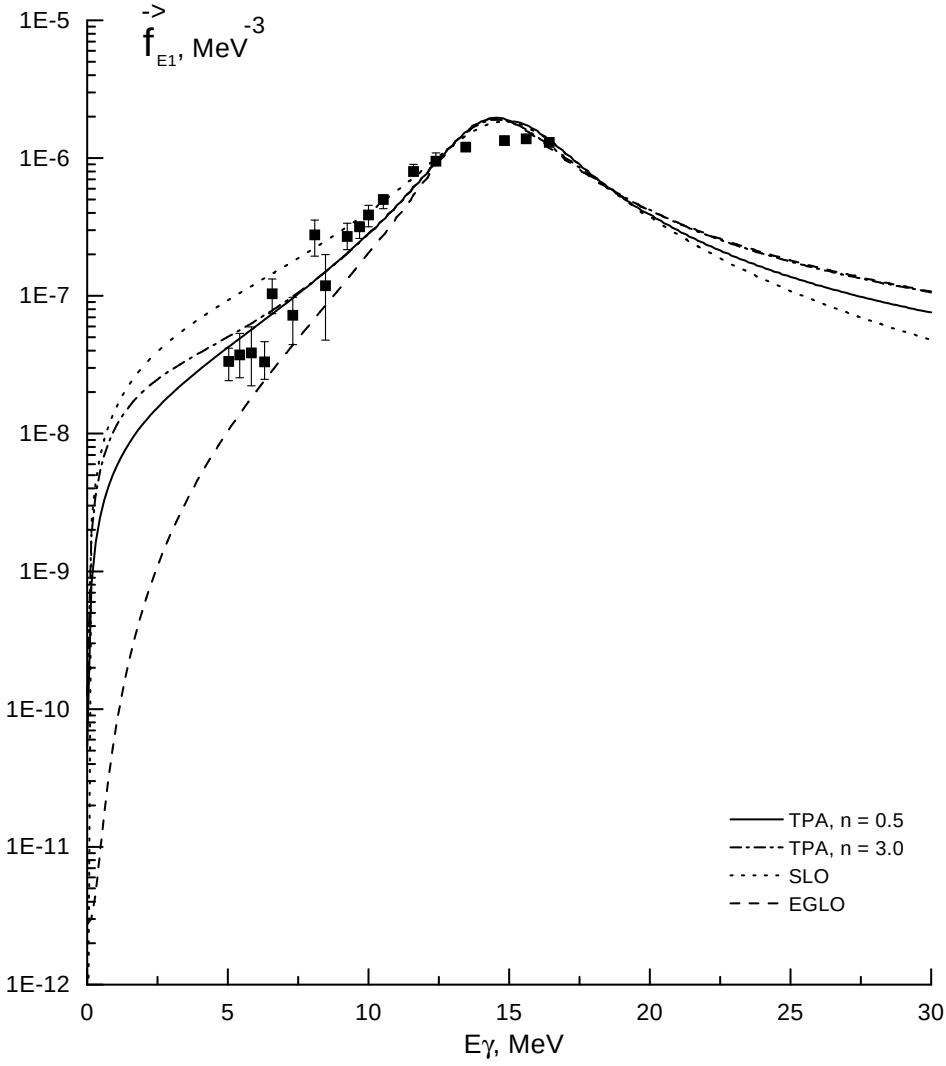

Fig. 4. The photoabsorption strength functions in Nd^{144}, T = 0.01 MeV.

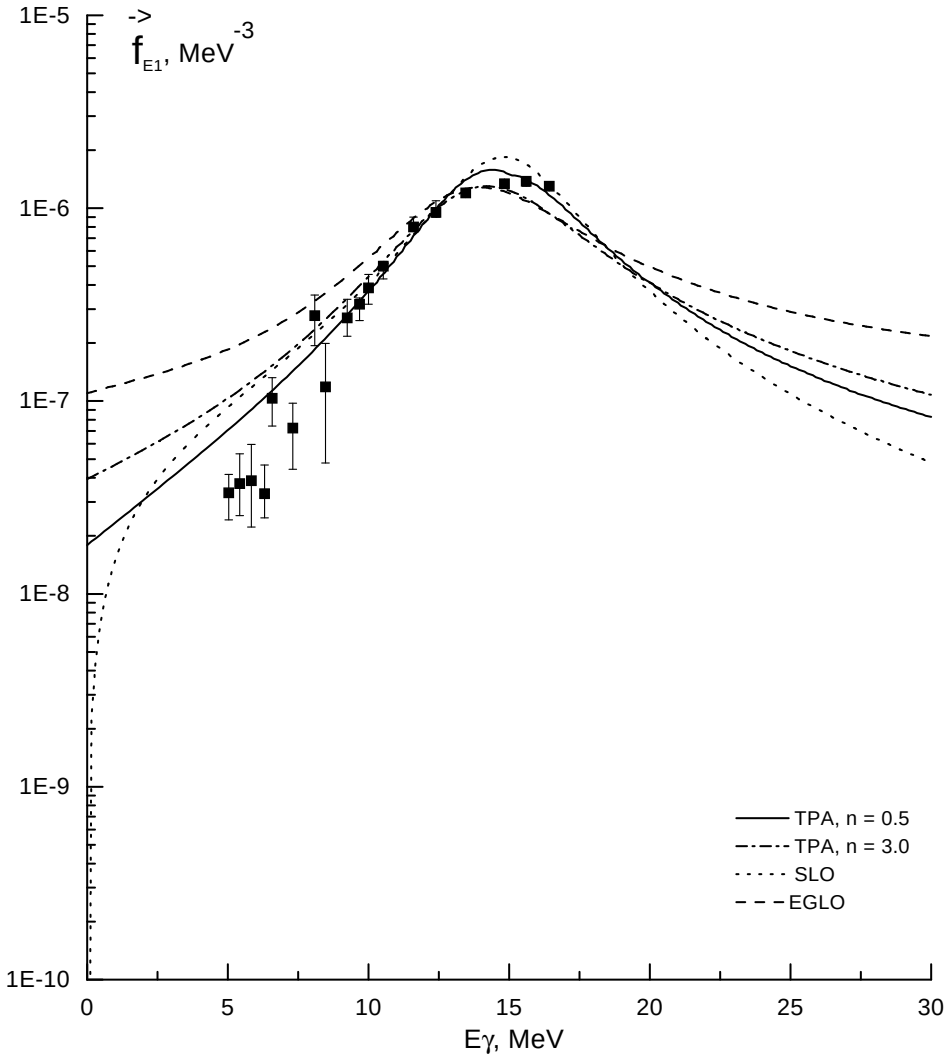

Fig. 5. The photoabsorption strength functions in Nd^{144}, T = 2 MeV.